A REMOTE CONTROL ELECTRONIC TORQUEMETER

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ABSTRACT. The paper gives details of observations on an electronic torquemeter. A rotating shaft transmitting mechanical power undergoes a twist which is measured in terms of time interval and number of revolutions per minute of the shaft. These two quantities can be measured from a remote distance with sufficient accuracy. The torquemeter described is suitable for both high and low speeds and does not impose any appreciable load on the rotating system. The stability of the torquemeter at high speed has been critically studied and details of design explained. The performance in measuring power transmitted by a rotating shaft has also been checked by comparison method.

INTRODUCTION

The various types of instruments that have been developed for measuring torque of a rotating shaft can be broadly classified as follows

(i) Mechanical devices based on concentric sleeve and disc displacement,

(ii) Electrical devices based on the change of inductance and capacitance and resistance of strain gauges,

(iii) Electronic devices based on the detection of electrical signal produced by changes introduced in the shaft due to torque.

Of these various types of instruments, those based on electronic detection are by far the most sensitive. However, complex electronic instruments which have so far been introduced (Dean and Kilburn 1955, Ainley 1948) have certain disadvantages and limitations, viz. (a) they are not suitable for both high and low speeds and (b) there is difficulty in accommodation of the detecting devices. These limitations have been obviated in a sensitive remote control electronic torquemeter designed by the present authors (Rakshit and Mukherjee 1955 and 1958).

As has previously been reported, in the new system two sharp pulses of voltage are produced in two magnetic pick-up coils due to the change in flux caused by two balanced blades of magnetic material fixed at a known separation on the rotating shaft. Initially, when the shaft is running free without any load and there is no twist in the shaft, the positions of the pick-up units are so adjusted that the two pulses occur at the same instant. In practice, the physical positioning does not require to be critically adjusted and the simultaneous occurrence of the

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two pulses at the measuring point is ensured by adjusting to zero the relative delay between the pulses after they have travelled through electrical delay systems A block schematic of the arrangement is shown in Fig. 1.

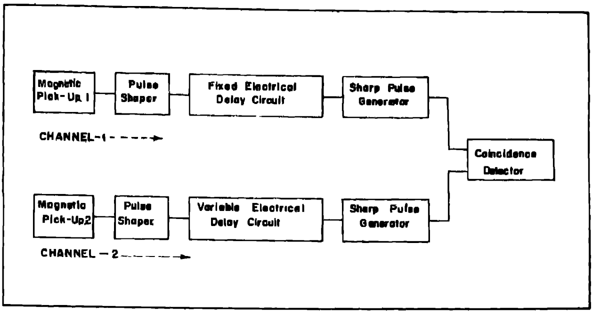

Fig. 1 Block diagram of the torquemeter

When the shaft transmits power, it will undergo a twist and as a result the pulses will be separated by a small interval of time which is dependent upon the angle of twist and the speed of rotation of the shaft This time interval T is given by

$$T = \frac{\theta}{6N} \text{ second}, \qquad \dots \quad (1)$$

where N = speed of the shaft (rev./min),

and θ = twist angle in mechanical degree between the two blade positions.

Coincidence is then restored by varying the delay, with the help of an accurately calibrated potentiometer, of one of the pulses with respect to the other The change in delay is obviously equal to T and this ultimately gives θ

ACCURACY OF THE MEASURING TECHNIQUE

The main problem in the electronic torquemeter is thus to measure the very small time interval between the two pulses and the number of revolutions per minute which, of course, is relatively quite easy For example, if $N = 15{,}000$ rev/min. and $\theta = 0.1°$, which is the permissible full load twist angle per foot of mild steel shaft, $T = 1.1$ microseconds approximately.

It is obvious that once coincidence is established, either in the rotating or in the non-rotating condition of shaft, it has to be maintained in order that the measurements may be reliable. Moreover the accuracy of measurement of a small time interval between two pulses is dependent upon the sharpness and also the duration of the pulses. The resolving time which is half the maximum time separation for which the pulses will remain coincident is obviously a function of the pulse width Special care has therefore been taken to develop suitable circuits for generating very sharp and stable pulses. The operation of the system under static condition of shaft which obviously depends only upon the electronic circuits has been found to be very stable. For this purpose the two pulses obtained from the pick-ups under dynamic condition of shaft were simulated by a single reference pulse obtained from (a) 50 cycle mains, as also from (b) 1Kc/s multivibrator This single pulse excited the two electronic delay channels The resolving time was found to be 0.02 μsec; a small amount of jittering could not, however, be avoided

The stability under rotating condition of the shaft depends upon both the electronic circuits and the rotating mechanical system including the associated magnetic pick-up devices The present paper gives a detailed account of the dynamic stability at both high and low speeds.

STABILITY TEST

For studying the stability of such an electronic torquemeter a high speed shaft unit was first constructed with two brass discs, 4 inches in diameter and 1/8 inch thick, fixed six inches apart on a 5/8 inch diameter shaft. Two projected and balanced mild steel blades were fixed on the two brass discs (Fig. 2) . The shaft

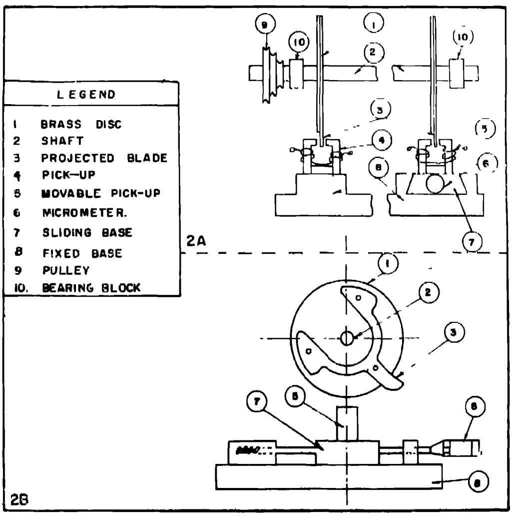

Fig 2 High speed shaft/unit with pick up devices. (A) Mechanical set-up, (B) projected blade and micrometer arrangement.

could be rotated at different speeds by a three phase a c motor through a *V*-belt and sets of pulleys. Initial observations showed that at low speeds the system works quite satisfactorily but at higher speeds considerable jitter is present This is due to the fact that in addition to the small amount of jitter due to electronic circuits, there are under dynamic conditions three main factors contributing to enhanced jitter These are :

(i) Vibration of projected blades due to intermittent resistance experienced by them in the pick-up gaps This vibration causes relative displacement between the blade and the associated pick-up and thereby increases the jittering.

(ii) Vibration of the *V*-belt due to the fact that the periodic air drag on the projected blades when they move through the pick-up air gaps introduces intermittent changes in the tension of the belt The non-uniform elastic property of the belt material throughout the belt also causes random change in tension of the belt which, in turn, produces non-uniform driving torque to the shaft by the belt and hence causes jittering.

(iii) Vibration of blade and pick-up due to magnetic interaction resulting from periodic linkage of the projected steel blade and the magnetic field in the pick-up gap.

The design of the bearing block used in the initial stages is shown in Fig 3. The leading edges of the blades were of course of special form to reduce air friction.

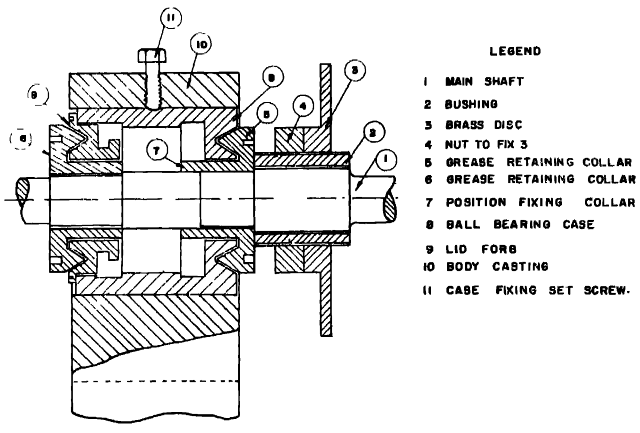

Fig. 3. Bearing block for shaft unit.

The pick-up units were rigidly fixed on a massive base and one pick-up could be moved at right angles to the shaft by micrometer arrangement (Fig 2B).

Instead of a twist produced in the shaft by load, it was simulated in the following way The two pick-up units are so positioned that the two pulses occur approximately at the same instant when the shaft is running free The initial delay in each channel is adjusted to a value near its minimum corresponding to the linear portion of the calibration curve giving delay against potentiometer reading The delay is controlled by means of a linear Helipot potentiometer fitted with a precision dial The shaft unit is then rotated without load and the delay in the variable channel so adjusted that the two output pulses occur simultaneously. The movable pick-up is then linearly shifted by 2-circular divisions of the micrometer in a direction opposite to that of the rotational direction of the blade near the pick-up and as a result the coincidence is lost. This shifting of the pick-up produced an equivalent twist θ between the two blades, given by

$$\theta = \frac{180d}{\Pi R} \text{ degree,} \qquad \ldots \quad (2)$$

where d = linear displacement of the pick-up
and R = effective radius of the blades

Coincidence is then restored by increasing the delay in the channel corresponding to the movable pick-up Owing to finite width of the coinciding pulses and some unavoidable jittering and flutter in the blades it was not possible to realize sharp coincidence with very small resolving time as will be seen from the results given below .

Incidentally, this gives us a method of finding the effective radius R Thus if the delay potentiometer is calibrated and the delay for one dial division of the potentiometer is K and the change in dial reading for restoring coincidence is A divisions then the delay is KA and from equations (1) and (2) we have

$$R = \frac{30d}{\Pi NKA} \qquad \ldots \quad (3)$$

Results of initial observations

As already pointed out the resolving time was not as small as desired but flickering coincidence was detected over a certain range of the Helipot dial as given in Table I

It should be noted that the scatter in the coincidence reading, e.g., between 160 and 277 for the initial potentiometer reading for r.p.m. 3060 is partly due to (a) the jittering between the channels (Fig. 1) and resolving time for coincidence, and is largely due to (b) the fluctuation of torque between the two blades and the vibration of the blade and pick-up as explained above. In regard to (a) it is of

TABLE I

$d = 2$ circular divisions $= 0.002$ inch, $K = 10.4$ nanoseconds/division

Rev/Min	Potentiometer Reading: Initial Range	Initial Mean	Final Range	Final Mean	Difference	Average (A)	θ (degree)	R (inch)
3060	160, 277	218.5	355, 530	442.5	224	223	0.0426	2.691
	170, 283	226.5	357, 540	448.5	222			
5800	160, 264	212	280, 382	331	119	119	0.0430	2.661
	175, 287	231	293, 407	350	119			
9660	160, 260	210	235, 335	285	75	74.5	0.0449	2.535
	181, 271	226	253, 347	300	74			

the order of 0.02 μsecond as observed when the reference pulse was applied directly to the delay circuits; this increases to 0.03/0.04 μsecond when the two pulse shaping channels are introduced as indicated in Fig. 1. The fluctuation of torque (b) originates from the pulsating "air-drag" and "magnetic drag" jointly in each narrow gap of the pick-up, and is also due to vibration of the V-belt system. The air drag is likely to increase with speed up to a certain limit while the magnetic drag is expected to decrease since the duration of magnetic interaction between blade and pole piece will decrease with increasing speed. On account of the inertia of the rotating disc assembly it is likely that the vibration due to V-belt driving system will be less at higher speeds. The overall jitter at any speed will be given by the resultant effect of all these causes. It will be noticed from Table I that within the range of observation, the scatter in coincidence decreases with increasing speed. Thus, for initial coincidence, the scatter is 115[$= \frac{1}{2}\{(277-160)+(283-170)\}$] divisions at 3060 rev/min, 108 divisions at 5800 rev/min and 95 divisions at 9660 rev/min. Although the scatter in coincidence reading decreases, the corresponding flutter $\delta\theta$ in twist angle increases with speed. Thus from equation (1)

$$K = \frac{\delta\theta_1}{A_1 N_1} = \frac{\delta\theta_2}{A_2 N_2} = \frac{\delta\theta_3}{A_3 N_3},$$

where
$$A_1 = 115 \text{ at } N_1 = 3060 \text{ rev/min}$$
$$A_2 = 108 \text{ at } N_2 = 5800 \text{ rev/min}$$
$$A_3 = 95 \text{ at } N_3 = 9660 \text{ rev/min.}$$

This gives $\delta\theta_1 : \delta\theta_2 : \delta\theta_3 = 3.519 : 6.264 : 9.179$, i.e., $\delta\theta_3 > \delta\theta_2 > \delta\theta_1$, which shows that the pulsating torque increases with speed

Moreover it has been observed that a considerably larger amount of power is required for driving the shaft with projected blades to overcome the steady frictional resistance due to air when the speed is increased from 3060 to 5800 r.p.m. It has further been noticed that when the projected part of the blade is reduced from 1.5 inch to 1 inch, this extra driving power becomes very small. The design of the rotating discs and the shaft unit had therefore to be modified as described below.

Modified design of rotating disc and shaft unit :

The modified design is given in Fig. 4 and the special features are the following :

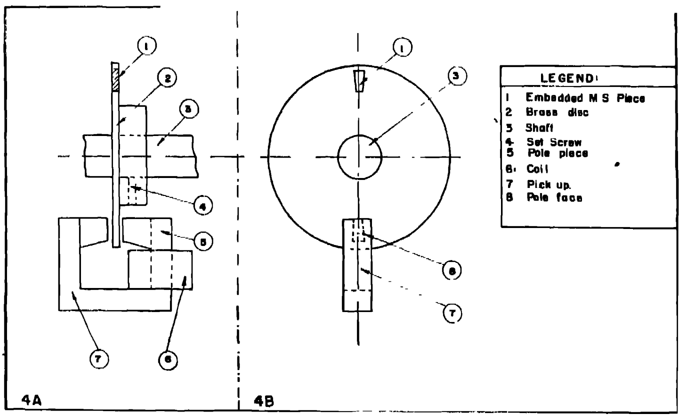

Fig. 4 Modified design of disc and pick-up (A) Front elevation, (B) Side elevation

(i) *Blade* To avoid air friction on the rotating projected blades and vibrations set up therein due to magnetic interaction in the pick-up pole pieces each blade was replaced by a small mild steel piece (3/8″ × 3/16″ × 1/8″ thick) embedded 1/8″ inside the periphery of the brass disc ($3\frac{1}{4}$″ × 1/8″ thick). The flat surfaces of the discs were highly polished to minimise air friction on the rotating discs.

(ii) *Pick-up.* The air gap in the pole piece of the pick-up previously used was $\frac{1}{4}$ inch and the intensity of magnetic field in the gap was 5700 gauss. The interaction between the rotating blade and this magnetic field produces vibration not only in the blade but also in the base and body of the pick-up For better stability of performance, which is very important for high-speed operation, since for the same torque θ the time interval T decreases with increasing speed, the construction of the pick-unit is to be more rigid. In the modified design a U-shaped permanent magnet with screwed pole piece has been used The pole faces are $3/8'' \times 3/16''$ with $1/4''$ air gap (Fig. 4A). The intensity of magnetic field in the air gap of the modified pole piece has, however, been much less, about one-tenth of the previous value The rigid construction of pick-up, the embedded blade system combined with reduction of magnetic field, considerably minimised the vibration problem The scatter in potentiometer reading for coincidence reduced to about 15 divisions as against over 100 divisions in the previous arrangement.

(iii) *Pre-amplifier.* With the modified pick-up the amplitude of the pulses produced at a speed of 1500 r.p.m was only about 1 volt. A two channel pre-amplifier with cathode-follower output has therefore been used to get a negative pulse with flat top and sharp leading edge for driving the main amplifier in the electronic torquemeter at a remote distance The preamplifier is fed with a stabilised power supply.

Performance test with load

For testing the operation of torquemeter under load, the shaft unit was put in between a d c motor and a d.c. generator driven by the motor The principle of measurement of power transmitted by the shaft is based on Hopkinson's method of back-to-back test of d c. shunt machines in which the different losses and the efficiencies of the two d.c. machines can be ascertained precisely. It has been checked that during operation the mechanical power transmitted by shaft is equal to the mechanical power received by the generator. The method becomes simpler if the two machines are identical, i e of same rating, type and model.

In the experimental arrangement, the two identical d.c machines were coupled by means of a shaft 0 751 inch diameter and 10.5 inches long, the two discs with embedded blades being fixed $5\frac{9}{16}$ inches apart on the shaft (Fig 5). The tests were conducted at speeds near about 1500 r p m. The transmitted and received powers measured from electrical data gives torque in electrical units. This torque is compared with that estimated from mechanical data involving the twist angle θ measured by the shaft unit.

The diagram of connections of the Hopkinson's method is shown in Fig. 6. The field current I_4 of the driven machine working as a generator is so adjusted that at the operating speed the output voltage of generator is equal to that across motor armature. Under this condition the generator output is fed back to the motor armature. Assuming that the shaft unit is not absorbing any power, the mechanical power output of the motor becomes equal to the input to the generator, and the total losses of the two machines, i.e. no-load loss and copper loss, is provided by the supply mains. As shown in Fig. 6, the electrical power supplied to the combination of the two machines running in parallel is W, given by

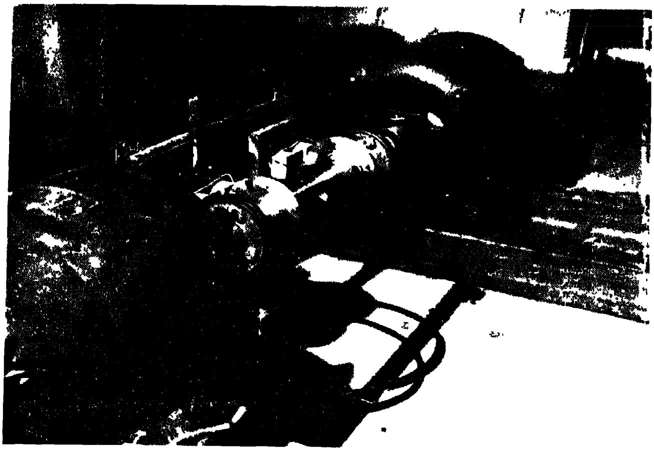

Fig. 5. Assembly view for performance test

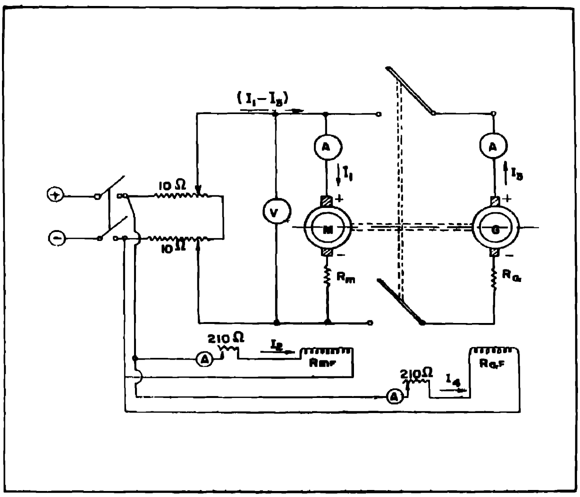

Fig. 6 Connection diagram for performance test.

$$W = (I_1 - I_3)V.$$

This power W consists of :

(i) No-load loss w of each machine,

(ii) Motor armature copper loss $w_1 = I_1^2 R_m$

(iii) Generator armature copper loss $w_2 = I_3^2 R_g$,

where R_m = motor armature resistance and R_g = generator armature resistance. The total no-load loss of the combination, which is equally shared by the two machines $= W - w_1 - w_2$ The no-load loss ω per machine is therefore given by $\omega = \dfrac{W - w_1 - w_2}{2}$

Now, power transmitted (P) in watts = motor output = generator input. And, motor output = motor input minus its losses, while generator input = generator output plus its losses. Hence

$$P = I_1 V - (w_1 + w) = I_3 V + (w_2 + w) \qquad \dots \quad (4)$$

The transmitted power thus estimated from electrical data is also equal to

$$\frac{2\,\pi\,T_R N}{12 \times 33{,}000}\ hp,$$

where T_R = torque produced in inch-pound
and N = rev/min.

Hence $$T_R = \frac{12 \times 33{,}000\,P}{746 \times 2\pi N} \qquad \dots \quad (5)$$

Again, in terms of mechanical data, T_R is given by

$$T_R = \frac{\pi^2 c d^4 \theta}{360 \times 16 l} = \frac{\pi^2 c d^4}{5760 l} \times 6NKA, \qquad \dots \quad (6)$$

where c = rigidity modulus in lbs/inch ²,

d = diameter of shaft in inch.

l = length of shaft between the two blades in inches as measured between the two fixing screws,

K = calibration constant = delay for one dial division of potentiometer,

A = change in helipot dial divisions for restoring coincidence.

For any given shaft therefore,

$$T_R = (\text{constant}) \times NA \qquad \dots \quad (7)$$

Comparison of T_R as given by equations (5) and (6) enables us to estimate the accuracy of torque measurement by the electronic torquemeter.

MEASUREMENT AND RESULTS

(i) *Rigidity Measurement* :

A shaft from same specimen of mild steel as used in Hopkinson method was tested in one Amsler Torsion Testing machine, to find out the rigidity modulus c, which comes out to be 11.44×10^6 lbs/inch^2.

(ii) *R.P.M. Measurement* :

Since the blade produces one pulse in one revolution, the r.p.m. is 60 times the recurrence frequency of the pulses per second. A simple method which has given very satisfactory results is shown in Fig. 7. Across the horizontal deflect-

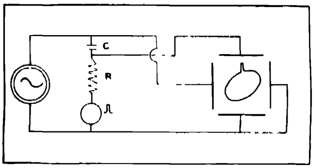

Fig. 7 Arrangement for speed measurement.

ing plates of a cathode ray tube the output of a calibrated audio oscillator is directly applied. Across the vertical deflecting plates we have the phase-shifted oscillator voltage in series with the pulse voltage Under these conditions we get on the C.R.O screen an ellipse on which is superimposed the pulse voltage moving round the periphery of the ellipse. When the pulse recurrence frequency is the same as that of the audio oscillator, a single stationary pulse is seen on the ellipse.

A second method, without utilizing a cathode ray tube, has also been used with good results The recurrent pulses derived from one of the pick-ups and pulses derived from a calibrated oscillator are applied to the grids of two valves having a common anode load resistance. A large output is obtained when the two pulses occur simultaneously. Details of the coincidence technique of measuring r.p.m. have already been described by the authors (Rakshit and Mukherjee 1955/2)

(iii) *Torque Measurement* :

The motor is run at desired speed by regulating the field current I_2 (Fig. 6). By controlling I_4, the output voltage of the generator is made equal to V and the two machines are put in parallel. The generator output current I_3 is now zero and the motor input current I_1 is used up in the motor armature copper loss w_1 plus the no-load losses $2w$ of the two machines

(a) For torque measurement from electrical data we have to measure, in addition to N and the different currents and voltage V, the values of R_m and R_g. These armature resistances are determined at room temperature and corrections made for rise in temperature under working conditions.

(b) For torque measurement from mechanical data we have to measure, in addition to c, d, l, N and K, the change A in delay potentiometer reading between no-load and load conditions With the shaft unit put in-between the motor and generator we do not get the no-load condition and the change A required as per equation (6) is obtained as follows

Initially when I_3 is zero, as stated above, only a very small torque is present in the shaft The variable delay in the appropriate channel is adjusted for initial coincidence and the Helipot reading is noted Due to flickering coincidence, two extreme readings are taken to obtain a mean value, say A' The transmitted power P is then increased by increasing I_3 which, in turn, is obtained by varying I_4, keeping V and N constant The new Helipot reading is then noted This is repeated for different values of transmitted power and also for different values of N.

It will be noted that for a given value of N, the plot of T_R or H.P. transmitted against A will be a straight line passing through the origin. Now if for $N = N_1$, the initial no-load coincidence corresponds to A_0 and the potentiometer reading

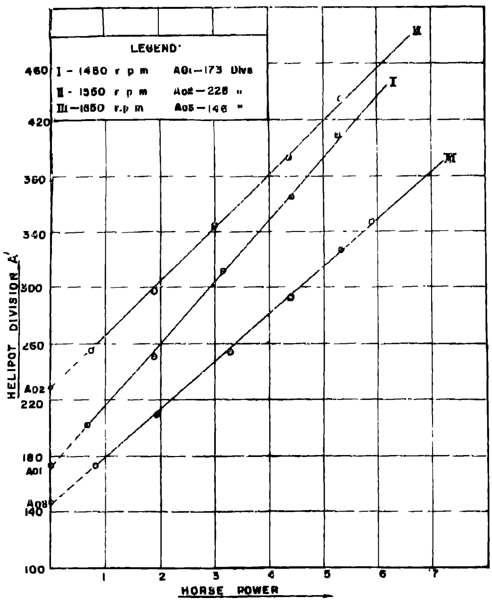

Fig. 8. Graph of transmitted power vs. Helipot division.

under load is A', the corresponding value of A is $A'-A_0$. Hence the straight line plot of H.P. transmitted T_R against A' will give an intercept A_0 on the A' axis. Fig 8 gives the values of A_0 for different values of N and these are shown in Table II. The values of torque estimated from electrical data as also from mechanical data for different operating conditions are presented in Table II.

TABLE II

$d = 0.751$ inch, $l = 5\frac{9}{16}$ inch; $K = 10.4$ nanoseconds/division, $c = 11.44\times 10^6$ lbs/inch^2

R.P.M.	Transmitted H P.	Torque measured from eqn(5) in Inch-Pound	Helipot Reading A′	A_0 from Fig 8.	Difference $A = (A'-A_0)$	Torque measured from eqn.(6) in Inch-Pound
1650	.0816	3 116	172.5	146	26 5	3.058
	1941	7.410	209 5		63 5	7 328
	3294	12.576	253.0		107 0	12 35
	4392	16.769	292.5		146.5	16.90
	5315	20 293	327.0		181 0	20.88
	5881	22 454	346 5		200.5	23 14
1550	0729	2.963	255 0	228	27.0	2.927
	1887	7.670	297.0		69.0	7 478
	2987	12 141	343 0		115.0	12.47
	4359	17 718	392.0		164.0	17.77
	5333	21.677	434 0		206.0	22.33
1450	.0669	2.906	202 0	173	29.0	2 941
	.1863	8.093	250.5		77.5	7.859
	3149	13.681	311.0		138.0	14 00
	4401	19.121	364.0		191.0	19 360
	5284	22 958	408 0		235.0	23.83

DISCUSSION

The results of observations as given in Table II show that the torque obtained from the torquemeter is in very close agreement with that obtained by the Hopkinson's electrical method The measurements were unfortunately limited to speeds round about 1500 r.p.m. since the two electrical machines used in the Hopkinson's test were designed for such low speed.

Other torquemeters have some inherent damping and are consequently rather sluggish in operation. They give a fairly steady average value even when the torque is fluctuating, i.e., short time variations in torque go undetected. The present torquemeter can however detect such temporary variations. The electronic circuitry can, of course, be easily modified to measure average torque when necessary. An additional advantage of this torquemeter is that practically no extra load is imposed on the system.

The coincidence has not been very sharp and there is a definite range over which the coincidence takes place. This scatter in coincidence does not depend upon transmitted power and within the speed range of observation the scatter decreases with increasing speed. This is expected since at higher speeds the impulse given to the vibrating system when the magnetic blade passes through the pick-up is of shorter duration resulting in reduced vibration

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REFERENCES

Ainley, D G , 1948, *Proc I Mech E* **159**, 240.

Dean, S K. and Kilburn, M A , 1955, *The Engineer*, **200**, 686

Rakshit, H and Mukherjee, S C , 1955/1, *J Sci. Industr Res.*, **14B**, 304.

Rakshit, H and Mukherjee, S. C , 1955/2 *J Inst Telecom Engrs* , **1**, 130

Rakshit, H. and Mukherjee S C , 1958, *Electronic Engineering*, **30**, 557.